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著者	Yoshikawa M., Yasuhara R., Morimoto M., Shima Y., Kohagura J., Sakamoto M., Nakashima Y., Imai T., Yamada I., Kawahata K., Funaba H., Minami T.
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Development of polarization-controlled multi-pass Thomson scattering system in the GAMMA 10 tandem mirror[a]

M. Yoshikawa,[1,b] R. Yasuhara,[2] M. Morimoto,[1] Y. Shima,[1] J. Kohagura,[1] M. Sakamoto,[1] Y. Nakashima,[1] T. Imai,[1] I. Yamada,[2] K. Kawahata,[2] H. Funaba,[2] and T. Minami[3]
[1]*Plasma Research Center, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan*
[2]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*
[3]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

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In the GAMMA 10 tandem mirror, the typical electron density is comparable to that of the peripheral plasma of torus-type fusion devices. Therefore, an effective method to increase Thomson scattering (TS) signals is required in order to improve signal quality. In GAMMA 10, the yttrium-aluminum-garnet (YAG)-TS system comprises a laser, incident optics, light collection optics, signal detection electronics, and a data recording system. We have been developing a multi-pass TS method for a polarization-based system based on the GAMMA 10 YAG TS. To evaluate the effectiveness of the polarization-based configuration, the multi-pass system was installed in the GAMMA 10 YAG-TS system, which is capable of double-pass scattering. We carried out a Rayleigh scattering experiment and applied this double-pass scattering system to the GAMMA 10 plasma. The integrated scattering signal was made about twice as large by the double-pass system. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4734490]

I. INTRODUCTION

The Thomson scattering (TS) diagnostic is one of the most reliable methods for measuring electron temperature and density profiles in fusion plasmas. However, in low-electron-density plasmas of less than 10^{19} m^{-3}, such as the GAMMA 10 plasma and peripheral plasma of high-density fusion devices, an effective TS system has yet to be developed.[1,2] A novel configuration for a multi-pass TS system is proposed for the improvement of time resolution and accuracy of electron temperature measurements by using the polarization control technique.[3,4] This configuration can realize a perfect coaxial multi-passing at each pass. This new multi-pass TS system is being developed in the GAMMA 10 tandem mirror. This multi-pass TS scheme effectively increases the scattering signal intensity from low-density plasmas. It allows a laser pulse to be focused several times onto the scattering volume to increase the number of scattering photons. Multi-pass TS systems have been demonstrated with many devices. At the tokamak experiment for technology oriented research (TEXTOR), the signal-to-noise (S/N) ratio was improved by using a multi-pass TS system, which uses a pair of concave mirrors to recycle photons.[5] In the JT-60U, a double-pass system was constructed using a phase-conjugate mirror for reflection.[6] Although these approaches have increased the reliability of the TS system, they are limited by the optical system. Each laser beam pass is different in the concave-mirror-type TS system in TEXTOR. The scattering volume must be set near the focal point of the concave mirror, and the system needs to be calibrated for each different beam pass. Moreover, the phase-conjugate-mirror system in JT-60U requires high purity laser bandwidth and polarization.

In this paper, we present a new scheme for a multi-pass TS system that uses polarization optics, and we demonstrate the results of the double-pass TS system installed in GAMMA 10. This scheme can be implemented by modifying a basic single-pass TS system with the addition of polarization devices, a high-reflection mirror, and lenses for the image relaying of the laser beam.

II. DESIGN OF THE POLARIZATION-CONTROLLED MULTI-PASS SYSTEM

A schematic diagram of the new multi-pass method for a polarization-based system is shown in Fig. 1. This system is based on the GAMMA 10 TS system, which has been used to successfully observe the electron temperature and density of GAMMA 10 plasma.[1,2] Horizontally polarized laser light from the yttrium-aluminum-garnet (YAG) laser (Continuum, Powerlite 9010, 2 J/pulse, and 10 Hz) is focused onto the plasma center by the first convex lens (Shigmakoki, $f = 2000$ mm, $\phi = 50$ mm) from the downside port window, which has an anti-reflection coating, after passing a short-pass mirror (CVI, SWP-45-RS1064-TP633-PW-2025-C), two Faraday rotators (EOT, HP-12-I-1064-000-000) for isolation, a half-wave plate (CVI, QWPO-1064-08-2-AS10), mirrors (CVI, YH-2037-45), a polarizer (Glan-Laser Calcite Polarizer), and an iris (Thorlabs, ID25/M). After interacting with plasma, the laser light is emitted from the upper side port window, which has an anti-reflection coating and collimated by the second convex lens (Shigmakoki, $f = 2000$ mm, $\phi = 50$ mm). A pair of lenses form a key component of this

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[b]Electronic mail: yosikawa@prc.tsukuba.ac.jp.

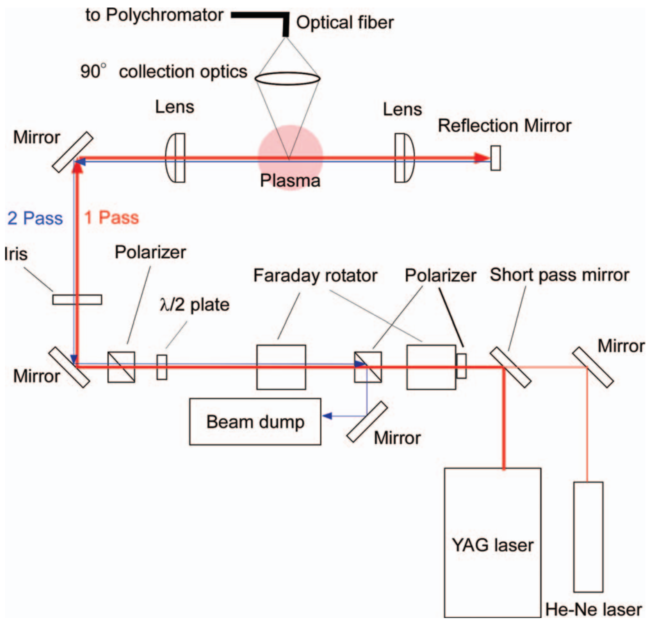

FIG. 1. Schematic diagram of the new multi-pass method of the polarization-based system.

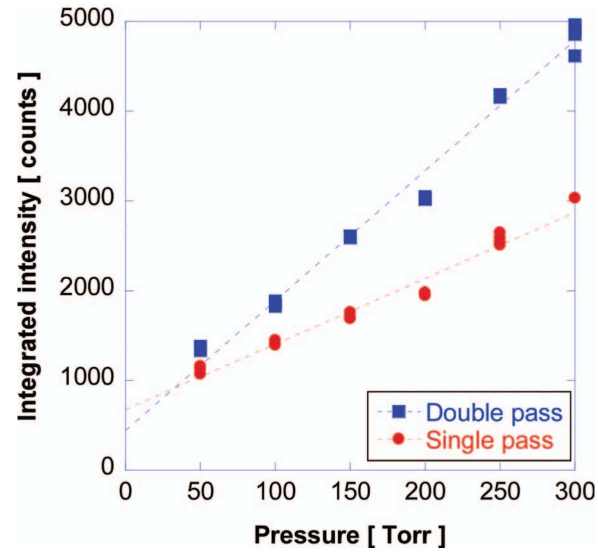

FIG. 2. Intensities of single-pass and double-pass signals from Rayleigh scattering measurements as a function of target pressure.

optical system. They maintain the laser beam quality during the multi-pass propagation through the image-relaying optical system from the iris to the reflection mirror. Laser light is reflected by the reflection mirror (CVI, Y1-1037-0) for the second pass and focused again onto the plasma. A Faraday rotator is used for polarization control. It switches the polarization of the laser light from horizontal to vertical for the second pass. Vertically polarized laser light is absorbed by the beam dump. The third laser pass is produced by a Pockels cell for polarization control and a reflection mirror. Then, the laser light is confined between the first and second reflection mirrors for the multi-pass propagation. For the TS light collection optics, we used an Al:SiO_2-coated spherical mirror with a curvature radius of 1.2 m and a diameter of 0.6 m. The scattered light is collected by the spherical mirror and reflected, after which it reaches an optical fiber bundle with a cross-section of 2×7 mm^2. The magnification factor of the collection optics is 2.2. The length of the scattering volume along the laser path is 15.4 mm, and the scattering angle is 90°. A solid angle of 0.078 sr can be realized by the light collection optics. This value is larger than those achieved in other plasma devices, which are typically less than about 0.020 sr. The 6.67-m-long optical fiber bundle (Mitsubishi Densen, FS10-25301B) is connected to a 5-channel polychromator. The optical fiber bundle comprises 48 fibers each, with a core diameter of 400 μm and a very large numerical aperture of about 0.47. The fiber aperture should be located at about 0.873 m away from the spherical mirror. The polychromator comprises 5 relay and collection lenses, 5 interference filters, and 5 silicon avalanche photodiodes (EG&G, C30950-CD1161). A four-channel high-speed oscilloscope (Tektronix, DPO4034B) is used to measure four wavelength channels simultaneously with a bandwidth of 350 MHz and a sampling rate of 2.5 GS/s. The measured signals are recorded by a Windows PC with LabVIEW analyzing software.

III. EXPERIMENTAL RESULTS

Rayleigh calibration experiments are carried out for setting up the optical system and measuring stray light in the evaluation of the double-pass GAMMA 10 YAG-TS system. Nitrogen gas is used, and the pressure in GAMMA 10 device is increased to 300 Torr. In Fig. 2, the intensities of integrated Rayleigh scattering signals from a single pass (red close circles) and a double pass (blue closed squares) as a function of target pressure are shown. The measured scattering signal is proportional to the gas pressure. The scattering intensity of the double pass is about twice as large as that of the single pass. The scattering signal intensities depend on the gas pressure and injected laser power. In the double-pass system, the scattered signals from the first and second laser passes are added. Therefore, the signals from the double-pass system improve with the increase in pressure over those from the single-pass system.

Next, we apply this double-pass TS system to electron temperature measurements. The plasma is produced during heating by ion cyclotron heating (ICH) from $t = 51$ to 240 ms. Typical electron line density of GAMMA 10 plasma is about 4×10^{17} m^{-2}. We measured the electron temperature at $t = 109.9$ ms. Figure 3 shows the double-pass (blue lines) and single-pass (red dotted lines) TS signals of Ch.1 (a), Ch. 2 (b), Ch. 3 (c), and Ch. 4 (d) after passing through a 200-MHz low-pass filter. From these results, the peak scattering signals from the double-pass configuration are found to be 1.6 times as large as those from the single-pass configuration. The integrated scattering signals are about twice as large as those from the single-pass configuration. In the GAMMA 10 YAG-TS system, the electron temperature is deduced by a nonlinear least-squares fit procedure using the integrated output signals of each channel. The fit is obtained by using a look-up table, which contains the calculated intensities expected in each channel at 1 eV intervals for up to 200 eV. The values for the

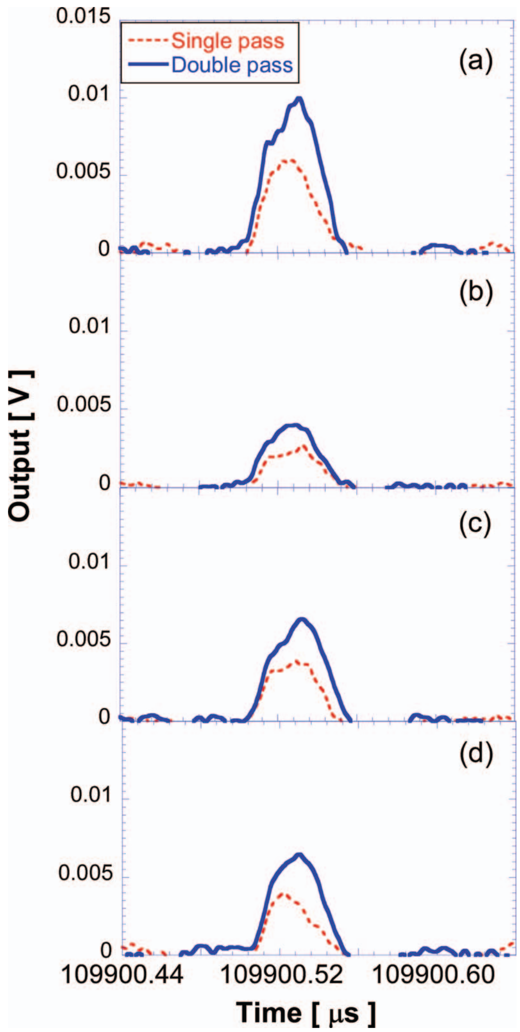

FIG. 3. Double-pass (blue lines) and single-pass (red dotted lines) TS signals of Ch.1 (a), Ch. 2 (b), Ch. 3 (c), and Ch. 4 (d).

electron temperature that minimize the chi-squared value are obtained by interpolating between the tabulated values. We used four channels to calculate electron temperature. Figure 4 shows the calculated chi-square values against the electron temperature of the single-pass (dotted line) and double-pass (bold line) systems. The electron temperatures obtained from the double-pass and single-pass TS systems are 32 ±1 eV and 30 ±3 eV, respectively. It can be noted that they are almost the same. The S/N ratios of double-pass system and single-pass system are about 6 and 3, respectively, because the two laser injections lead to the achievement of twofold signal intensity in the double-pass system. The electron temperatures calculations performed using the chi-square method show less than half the number of errors in the double-pass system. This shows the improvement in data quality of the GAMMA 10 TS system and the feasibility of the proposed polarization-based multi-pass system.

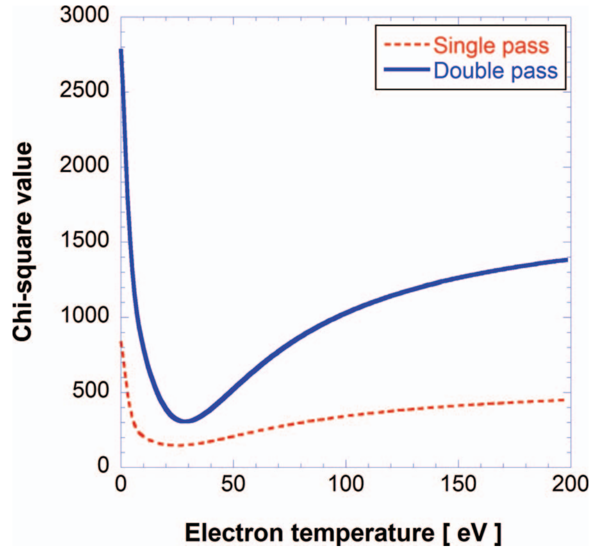

FIG. 4. Calculated chi-square values against electron temperature of single-pass (dotted line) and double-pass (bold line) systems.

IV. SUMMARY

A novel configuration of the multi-pass TS system is proposed for improving the time resolution and accuracy of electron temperature measurements by using the polarization control technique. The double-pass TS system was shown to improve TS signal intensity for better data quality in TS experiments. We are developing this new multi-pass TS system in GAMMA 10 to increase the number of passes.

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